II.5 Solid State Energy Conversion Alliance (SECA) Solid Oxide Fuel Cell Program

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Objectives

- Develop a fuel-flexible and modular system (3 to 10 kW) that can serve as the basis for configuring and creating low-cost, highly efficient, and environmentally benign power plants tailored to specific markets.
- Demonstrate a prototype system of the baseline design with desired cost projections and required operating characteristics (Phase I); assemble and test a packaged system for a selected specified application (Phase II); field test a packaged system for extended periods (Phase III).

Approach

<u>(Phase I)</u>

- Establish a baseline system concept and analyze its performance characteristics.
- Perform a study to estimate system costs.
- Develop a robust, reliable, high-performance solid oxide fuel cell (SOFC) stack technology amenable to low-cost manufacturing.
- Develop a fuel processor as a pre-reformer for processing a variety of fuels.
- Evaluate system thermal management to establish a suitable recuperation scheme for the system.
- Develop and implement a flexible control structure incorporating required sensors.
- Identify a flexible, low-cost power management subsystem.
- Evaluate component integration.
- Design, assemble and test a prototype system to demonstrate performance meeting the program requirements.

Accomplishments

Key accomplishments in FY 2005 are summarized below.

- System Design and Analysis
  - The prototype system design, including analysis of its performance, was completed. The analysis indicated that the efficiency target of 35% could be reached or exceeded by this design.
- Cost Estimate
  - Projected cost estimates were updated and a cost report submitted and audited. High-volume manufacturing costs for the prototype system were estimated based upon actual prototype system performance and hardware cost estimates. From these data, a total system cost of \$724/kW (5.4 kW basis) was calculated. This estimate is below the projected cost requirement of \$800/kW for Phase I of the project.

- Stack Technology
  - High power densities of 0.36 W/cm^2 (0.52 A/cm^2 at 0.7 V) and 0.34 W/cm^2 (0.48 A/cm^2 at 0.7 V) have been achieved at 80% and 88% fuel utilizations (FU), respectively, with simulated autothermal reforming (ATR) gas (32.2% H_2, 6.8% CH_4, 8.4% CO, 5.8% CO_2, 29.8% N_2, 17% H_2O) for single-cell modules.
  - Multi-cell stacks up to 40 cells have been assembled and tested and have demonstrated highly efficient performance on both dilute hydrogen and ATR surrogate. For example, a 40-cell SOFC stack with 16-cm diameter cells achieved 1.40 kW at 0.428 A/cm^2 with 80% fuel utilization and an average cell voltage of 0.673 V (44.7% stack efficiency) using simulated ATR reformate.
  - A number of 20-cell stacks were built and tested to improve both cell-to-cell and stack-to-stack reproducibility. At all operating conditions, the power of each stack was within 5% of the mean power.
- Fuel Processing
  - An ATR pre-reformer integrated with a 3-cell SOFC stack has been operated at 0.400 A/cm^2, 73% fuel utilization and has performed stably for approximately 2400 hours.
- Control
  - A control system was designed and implemented for the SECA prototype system. The control strategy is composed of a top-level supervisory control structure and lower-level active controls. The supervisory controls provide load management, operating mode management, and built-in test for online diagnostics and error handling. The lower-level active control loops provide setpoint tracking for flows and temperatures throughout the system.
- Balance of Plant (BOP)
  - Bill of materials was developed and completed for BOP components. Several components were designed and custom made for the prototype (e.g., cathode air blower, power electronics, heat exchangers), and others were off-the-shelf components selected and validated for suitability for the prototype system.
- Prototype Assembly
  - A prototype system design was completed, including system schematic, package drawing, bill of materials, and heat and material balances.
  - A prototype was built and has been tested according to the test plan.
  - The system has achieved a peak efficiency of 40.9% (exceeding the SECA target of 35%) and peak DC net power of 5.43 kW.

Future Directions

- Prototype testing will continue and will be completed at GE Hybrid Power Generation Systems (GE HPGS) according to the test plan.

Introduction

This project focuses on developing a low-cost, high-performance solid oxide fuel cell (SOFC) system suitable for a broad spectrum of power generation applications. The overall objective of the project is to demonstrate a fuel-flexible, modular 3-to-10-kW system that can be configured to create highly efficient, cost-competitive, and reliable power plants tailored to specific markets. The key features of the SOFC system include a fuel-flexible pre-reformer; a low-cost, high-power-density SOFC stack; integrated thermal management; and suitable control and power management subsystems. When fully developed, the system is expected to meet the projected cost of $400/kW.

Approach

The SOFC system is a stationary power module (3 to 10 kW) capable of operating on different fuels. The system consists of all the required components for a self-contained unit, including fuel cell stack, fuel processing subsystem, fuel and oxidant delivery subsystem, thermal management subsystem, and various control and regulating devices.

- The SOFC is a compact of anode-supported cells (fabricated by the GE HPGS tape-calendering process) and metallic interconnects. The stack design is based on an advanced concept that maximizes cell active area and minimizes sealing. The fuel cell can operate directly on light hydrocarbon fuels and incorporates materials for high performance at reduced temperatures (<800°C). These characteristics provide a low-cost, fuel-flexible fuel cell suitable for operating under various conditions. The tape calendering process for manufacturing thin-electrolyte, anode-supported cells is a potentially low-cost, mass-customization technique suitable for high-volume production and automation using available commercial equipment.
- The fuel processor is a catalytic reactor that functions as a pre-reformer. The system employs an integrated thermal management approach to utilize byproduct heat, reduce heat losses, and, consequently, increase the overall system efficiency. The system also has a flexible control structure that can be modified or optimized for different applications.

The project consists of three phases. Phase I of the project focuses on developing system components having the required operating characteristics, resolving critical technological issues, and demonstrating a prototype system. The Phase I work concentrates on system design and analysis, the cost study, stack technology development, fuel processing development, controls and sensors, power electronics, and system prototype assembly and testing. Phase II will demonstrate a packaged system selected for a specified application and further improve technology and assess system cost. Phase III will extend the Phase II effort to field test a packaged system for extended periods to verify the required performance, cost, reliability, and lifetime for commercial uses.

Results

System Design and Analysis

A conceptual design was developed for a natural gas-fueled, 3-10 kW SOFC system for stationary applications. The design included an autothermal reforming (ATR) fuel processor and a SOFC stack that can process light hydrocarbons internally (internal reforming). This system conceptual design served as the foundation for the detailed design of a prototype system that was subjected to various performance analyses. The effects of a number of critical performance factors such as SOFC stack performance, system heat loss, auxiliary power, and pressure drop were determined for the prototype system. From these analyses, it was determined that the efficiency target of 35% could be reached or exceeded by this design (Figure 1).

Cost Estimate

The system cost estimate study was completed, and the cost estimate report was submitted and audited. The cost estimate involved projecting the costs of the SOFC stack; fuel processor; fuel, air, and water delivery subsystems; thermal management; electrical system; packaging; and assembly. The system power rating was based on the demonstrated peak power of the prototype system. The total system cost projected in this study is $3910 assuming volume production of 50,000 units per year. Based on 5.4 kW peak power demonstrated in the prototype system testing, the total system cost estimate is $724/kW.

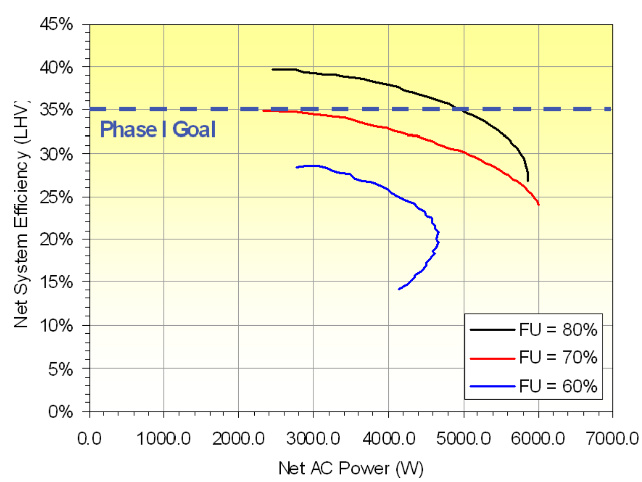

Figure 1. Prototype System Efficiency Projections

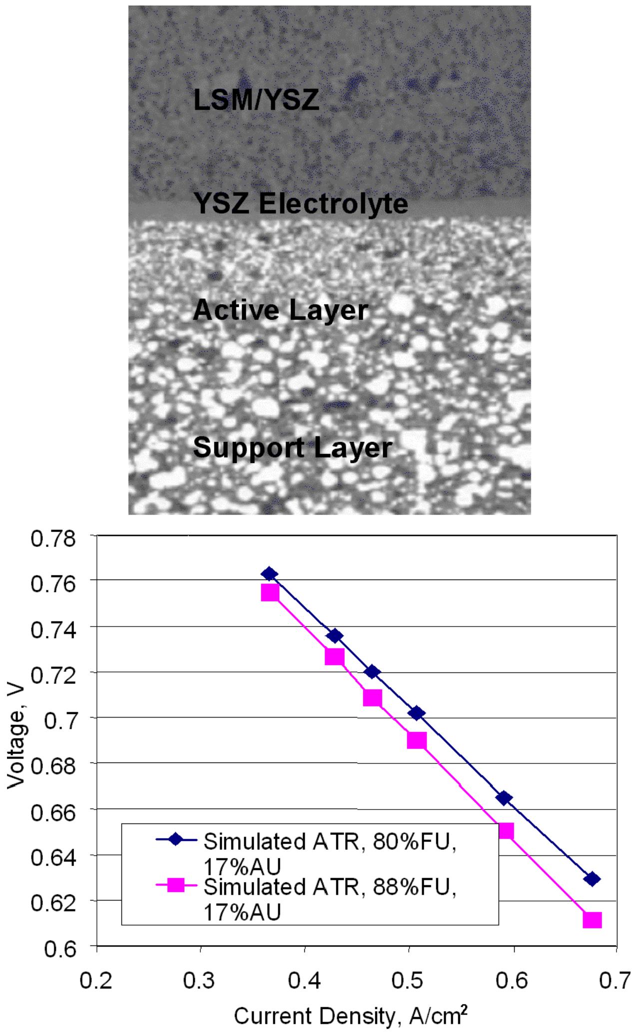

Figure 2. Typical Microstructure of Anode-Supported Cell and Cell Performance at 800°C with Simulated ATR Fuel (80% and 88% Fuel Utilization)

Stack Technology Development

Anode-supported cells up to 30 cm in diameter have been tested, and excellent performance has been demonstrated at fuel utilization levels suitable for practical applications. As an example, Figure 2 shows the microstructure of a 16-cm (6.3") diameter anode-supported cell and the typical performance of such a cell (tested as a single-cell module, i.e., a single-cell stack or a cell with anode and cathode interconnect flow fields). As can be seen from Figure 2, high power densities of 0.36 W/cm^2 (0.52 A/cm^2 at 0.7 V) and 0.34 W/cm^2 (0.48 A/cm^2 at 0.7 V) have been achieved at 80% and 88% fuel utilizations (FU), respectively, with simulated ATR

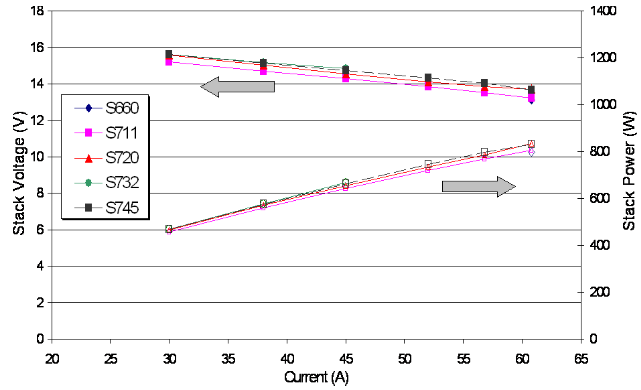

Figure 3. Performance of 20-Cell Stacks (Simulated ATR Fuel, 80% Fuel Utilization)

gas (32.2% H_2, 6.8% CH_4, 8.4% CO, 5.8% CO_2, 29.8% N_2, 17% H_2O). This cell architecture has demonstrated extraordinarily high fuel utilization for anode-supported cells. Fuel utilization up to 95% and stack efficiency greater than 55.5% have been realized using dilute hydrogen as fuel (800°C and ambient pressure stack operation).

Multi-cell stacks up to 40 cells have been assembled and tested and have demonstrated highly efficient performance on both dilute hydrogen and ATR surrogate. For example, a 40-cell SOFC stack with 16-cm diameter cells achieved 1.40 kW at 0.428 A/cm^2 with 80% fuel utilization and an average cell voltage of 0.673 V (44.7% stack efficiency) using simulated ATR reformate. In addition, a number of 20-cell stacks were built and tested to improve both cell-to-cell and stack-to-stack reproducibility. At all operating conditions, the power of each stack was within 5% of the mean power (Figure 3). At the design point of 0.428 A/cm^2 and 80% fuel utilization in simulated ATR fuel, the average cell power density reached 0.288 W/cm^2. This performance is sufficient to exceed the performance requirements of Phase I.

Fuel Processing

An ATR processor was designed and developed for the SECA system. Several prototypes were built based on the design, and their operation was evaluated. The fuel processor was tested extensively (as a stand-alone component and as an integrated SOFC stack/fuel processor subsystem) prior to incorporation into the system and was found to demonstrate the ability to meet the necessary system

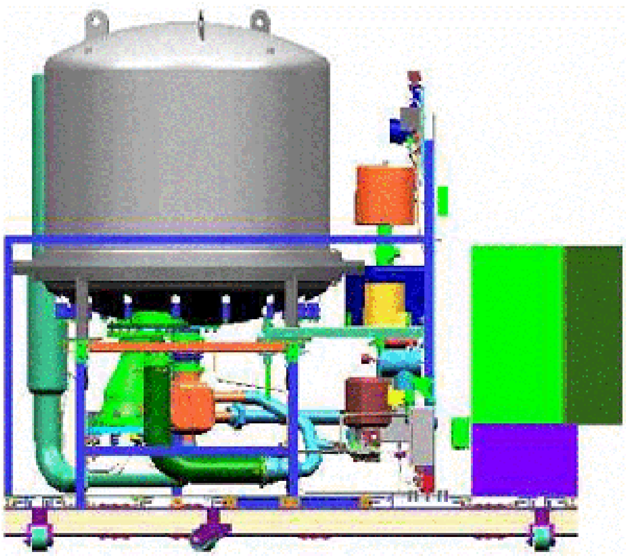

Figure 4. Prototype System

requirements (steam-to-carbon ratio, oxygen-to-carbon ratio, outlet reformate temperature, methane slip, pressure drop). A long-term test of a 3-cell SOFC stack integrated with an ATR has been conducted. The SOFC/fuel processor subsystem was operated at 0.400 A/cm^2 and 73% fuel utilization and has performed stably for approximately 2400 hours.

Control

A control system was designed and implemented for the prototype system. The control strategy is composed of a top-level supervisory control structure and lower-level active controls. The supervisory controls provide load management, operating mode management, and built-in test for online diagnostics and error handling. The lower level active control loops provide setpoint tracking for flows and temperatures throughout the system.

Prototype System

Figure 4 shows a conceptual packaging layout of the hardware for the prototype system. The system consists of the SOFC stacks and other components required for efficient operation on natural gas, including an ATR fuel processor used as a pre-reformer. The system was designed to allow component access so that it could be easily modified and improved during the various stages of integration that led up to the final system test. Many of the key system operating features (component/subsystem integration, thermal management including self-sustaining operation, and control subsystem including startup and shutdown) were verified using sub-scale SOFC stacks prior to the assembly and testing of the final prototype configuration. The final prototype system testing is currently underway. The system has achieved a peak efficiency of 40.9% and peak DC net power of 5.43 kW. The system is operating at the normal condition for the first steady-state hold period. At the completion of 1000 hours, the unit will undergo ten power cycles before operating for an additional 500 hours at the normal operating condition. At the conclusion of this period, a peak efficiency and peak power points will be repeated.

Conclusions

- A design of the SECA prototype system was developed. Analysis of the design showed performance exceeding the efficiency target of 35%.
- The results of the cost estimate study indicated a total projected system cost of $724/kW (5.4 kW basis). The estimate is below the projected cost requirement of $800/kW for Phase I of the project.
- SOFC single-cell modules and multi-cell stacks were built and operated and showed significant performance improvements. Multi-cell stacks showed performance sufficient to exceed the performance requirements of Phase I.
- A SOFC stack integrated with an ATR fuel processor has operated stably for approximately 2400 hours.
- A multi-level design for the control subsystem was developed and implemented in software for the prototype system.
- A bill of materials was developed and completed for the BOP components. Several components were designed and custom made for the prototype, and others were off-the-shelf components selected and validated for suitability for the prototype system.
- A prototype system was built and has been tested with hydrogen and methane. The key operating features of the prototype system were verified. The system has achieved a peak efficiency of

40.9%, exceeding the target of 35%, and peak DC net power of 5.43 kW.

FY 2005 Publications/Presentations

1. N. Minh, "Solid Oxide Fuel Cell Technology Development Status", 2004 Fuel Cell Seminar Extended Abstracts, Courtesy Associates, Washington, DC, 2004.
2. N. Q. Minh, "SECA Solid Oxide Fuel Cell Program", presented at the SECA 6th Annual Workshop in Pacific Grove, CA, April 18-21, 2005.
3. N. Q. Minh, "Solid Oxide Fuel Cell Systems for Stationary Power Generation Applications," in SOFC IX, Electrochemical Society, Pennington, NJ, 2005, p. 76.